Design of terahertz photonic crystal fiber and antenna

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Abstract: The design of a hollow-core terahertz photonic crystal fiber (PCF) based on poly methylmethacrylate (PMMA) is reported in this paper. THz wave propagates inside the core large hole and the surrouding four cladding layers with small holes can confine THz wave propagation. By simulation in software COMSOL, the leakage loss of the designed PCF is found to be lower than 0.1 dB/m at 0.6 THz which is low at terahertz band. Similar to the radiation theory of metallic waveguide, the PCF can also be used as antenna to radiate energy. Its radiation characteristics are simulated. The simulated input reflection coefficient is less than -25 dB and the directivity of the antenna is greater than 20 dB. The half power beam width is about 13 degrees.

Key words: terahertz; photonic crystal fiber; antenna; electromagnetic band gaps

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太赫兹光子晶体光纤与天线设计

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摘　要: 以聚甲基丙烯酸甲酯(PMMA)材料为基质,设计了一种空芯多孔包层结构的太赫兹光纤,中心的大孔缺陷用于传输太赫兹波,周围四层小孔可以将太赫兹波的传播限制在缺陷内部。利用 COMSOL 软件对光纤的损耗特性进行仿真分析发现,光纤在 0.6 THz 的泄露损耗低于 0.1 dB/m,具有良好的传输特性。和金属波导口可以当作天线辐射电磁波的原理相似,光纤的端面也可以作为天线将内部传输的太赫兹波向外辐射,通过仿真分析,天线在 0.59~0.61 THz 的回波损耗低于-25 dB,方向性系数大于 20 dB,半功率波束宽度约为 13°。

关键词: 太赫兹;　光子晶体光纤;　天线;　电磁带隙

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0 Introduction

The terahertz (THz) frequency range, located between microwaves and visible light, has been exploited in technical and fundamental research areas. The THz technical problems can be researched either in optics way or in microwaves way or in both ways. Whereas the THz technology is less applied in commercial occasions but mainly in particular cases due to the limited capability.

Researchers show intense interests in the propagation of THz guided wave and the associated coupling efficiency from THz free-space propagating waves to the guided wave. Because of the increasing demands for THz waveguides which can be applied in practical cases, kinds of THz waveguides that realize quasi-optical coupling have been proposed and demonstrated in recent years. Most of these structures are similar to the conventional guiding structures, such as metal tubes[1], plastic ribbons[2] or fibers[3]. In these conventional structures, the utility propagation of THz pulses is limited by their large transmission loss and the group velocity dispersion of guided waves[4-5]. Moreover the finite conductivity will lead to a high transmission loss. In several reported papers, the parallel metal plate waveguide is applied to propagate THz waves without dispersion. This seems to be the most promising technology to propagate THz waves, however the cross-section of the waveguide is too large for many application cases, particularly in medical diagnostics occasions. A bare metal wire can also be used to transmit terahertz pulses, but the guided mode could be perturbed by structures located close to the wire[6]. Reports on photonic crystal fibers (PCF) to propagate and radiate THz waves have been published lately[7-8]. The photonic crystal can be formed by periodically arranged dielectric and/or metallic structures. These structures have frequency band gaps at which the propagation of electromagnetic wave is forbidden in the crystal[9]. So the propagation of guided THz waves is realized typically by arranging multiple air-holes longitudinally along the photonic crystal fibers or microstructured optical fibers.

The first silica single-mode PCF was proposed and demonstrated in 1996[10], then it was quickly proved that PCF possess variable optical properties. Structures with solid-core and hollow-core PCF are reported by researchers[11]. The fiber with air holes can be made from a single material, the technology could be transferred from silica to any other transparent, drawable material to obtain mechanical and/or optical properties. The first non-silica single-mode PCF was made using polymer, a microstructured polymer optical fiber [12] made of PMMA. PMMA is a common material usually used in the fabrication of polymer optical fiber[13]. Another technique that may contribute to controlling the propagation of THz waves is designing a microstructured photonic band gap (PBG) fiber[14]. The PBG property is supported by periodic lattices in the cladding[15]. Similar to THz waveguides reported previously, the PBG fiber allow light to propagate along a hollow core. More recently, an alternative microstructured fiber with circular rather than hexagonal rings of holes was reported[16]. The circular rings of holes are intended to work as the low-index layers of a Bragg reflector in the cladding[17]. As much efforts have been done on solid-core waveguides, the hollow-core ones would bring lots of concerns

Antennas are fundamental elements to radiate and receive energy, so they are essential in THz systems. Various kinds of THz antennas are proposed and realized, such as dipole antenna, Yagi antenna, bow-tie antenna, lens-integrated antenna, metallic horn antenna, dielectric core horn antenna, corner reflector antenna, and carbon nanotube antenna[18]. Photonic crystals have wide range of applications in antennas: be used as antenna substrates to reject power radiation into the substrate side to enhance the gain of antennas [19]. Moreover, antennas can be directly formed by photonic crystal structures with channels into the crystal which have openings to free space. The idea has been realized by utilizing two dimensional metallic post array structures at optical band[20] and at 0.5 THz[20].

This paper is organized as follows: the terahertz PCF is introduced firstly. The transmission properties of THz wave in microstructured polymer waveguide with a hollow-core and the theoretical analysis are discussed secondly. Simulation results of antenna made of PCF including return loss and radiation patterns are presented thirdly, conclusions are obtained finally.

1 Terahertz photonic crystal fiber

Based on a triangular-lattice air-cylinder array in a dielectric background, an all-dielectric photonic fiber in circular shape is designed. According to the Bragg diffraction theory, the structure has electromagnetic band gaps in certain frequency bands. Thus wave propagation is prohibited within these band gaps and a hollow channel in the core of photonic crystal structure can confine and guide THz wave to be propagated along the channel. In this way, radiation loss in the propagation direction can be dramatically reduced due to the electromagnetic band gap cladding structure. Compared with conventional dielectric waveguides, the THz wave propagated in the designed structure has less material loss for the majority of the incident power is confined within the hollow core region.

Figure 1 (a) shows the cross-section of the all-dielectric waveguide. The structure has an air-hole hollow in the core and several surrounding air cylinders which follow a triangular lattice. Within the frequency band gaps, hollow modes present in the designed fiber will support efficient energy confinement and propagation. The fiber is composed of 19-unit-cell air holes in the core, and four cladding rings which contain several air holes in a two-dimensional (2D) triangular arrangement. The cladding structure parameters are as follows: hole-to-hole spacing pitch a=0.6 mm, air hole diameter d=0.5 mm, diameter of the hollow core D= 2.5 mm. The background material of the designed structure is PMMA (refractive index n=1.95), it has a small absorption coefficient below 1 THz. This waveguide design is completely scalable with the lattice constant. Using software COMSOL to simulate the Eigen-mode, we calculate the fields distribution of fundamental mode within the first band gap as illustrated in Fig.1 (b). According to the energy profile through simulation, this mode resembles a Gaussian distribution so that it can be excited by an incident linearly-polarized Gaussian beam.

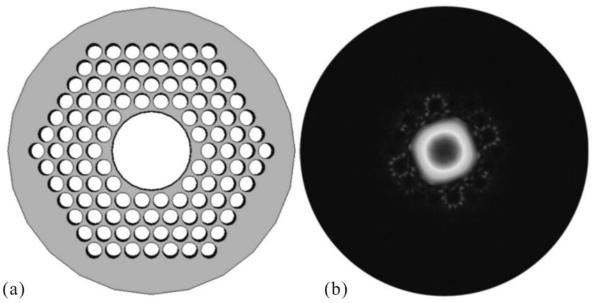

Fig.1 Schematic of the hollow core waveguide cross section and fields distribution of HE_{11} mode in the waveguide

To calculate the leakage loss, we apply the perfect matching layers (PMLs) condition outside the computation region. We also assume the dielectric constant of the PMMA to be real and the imaginary part of β to be only related to the leakage loss. The symmetry and anti-symmetry conditions are set according to the field distributions of guided modes to reduce the computation domain to one quadrant. Figure 2 shows the leakage loss of the HE_{11}-like fundamental mode: the minimum value of the HE_{11}-like fundamental mode is 0.07 at 0.6 THz. The width of frequency band gap is about 0.04 THz which illustrates good propagation confinement in the core.

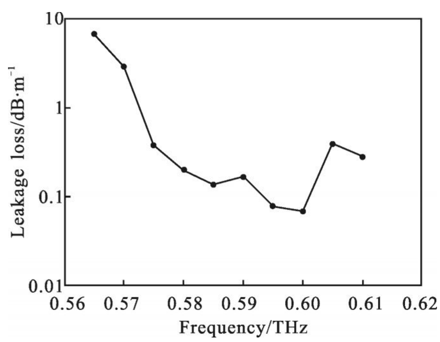

Fig.2 Leakage loss versus frequencies for HE_{11} mode

2 Photonic crystal fiber antenna

Just as a metallic waveguide which is applied as an antenna to radiate electromagnetic waves, the photonic crystal fiber can also be used as an antenna. This paper designed and simulated a fiber antenna, its simulation results are shown in Fig.3. From 0.56 to 0.62 THz, the input reflection coefficient S_{11} is less than −25 dB. The simulated directivity of the photonic crystal fiber antenna is shown in Tab.1: the directivity is about 22 dB from 0.59 to 0.61 THz. Figure 4 plots the simulated directivity pattern of the antenna at the cut plane $\varphi=0°$ and $\varphi=90°$, with sweeping from −180° to 180° at 0.6 THz. The boresight directivity is 22.6 dB with the half power beam 13°. The sidelobe is very small, about −30 dB.

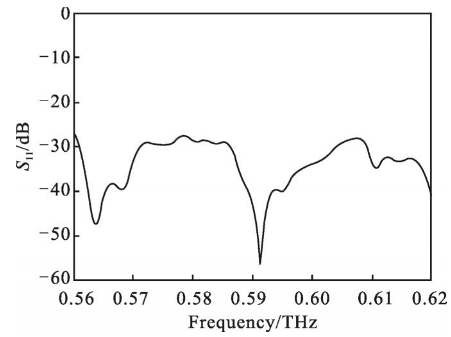

Fig.3 Simulated input reflection coefficient S_{11}(in dB) of the antenna

Tab.1 Boresight directivity of the fiber antenna at several frequencies

Frequency/THz	0.59	0.595	0.60	0.605	0.61
Directivity/dB	21.4	21.9	22.6	22.2	22.7

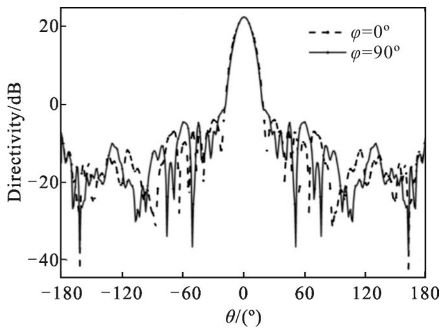

Fig.4 Radiation patterns of the antenna with θ sweeping from −180° to 180° at 0.6 THz

3 Conclusion

In this paper, a terahertz PCF and an antenna based on all-dielectric hollow-core photonic crystal structure is proposed and demonstrated. Simulation results show that the fiber possesses good propagation confinement and the antenna has good return loss over the simulated frequency range and high directional radiation pattern in the designed passbands. As an important free-space coupling component, the PCF antenna can be applied in future integrated THz systems.

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